20-GHz broadly tunable and stable mode-locked semiconductor amplifier fiber ring laser

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We present an actively mode-locked fiber ring laser that uses a single active semiconductor optical amplifier device to provide both gain and gain modulation from an external optical pulse train. The laser source generated 4.3-ps pulses at 20 GHz over a 16-nm tuning range and is stable against environmental changes and simple to build.

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Short-pulse high-repetition-rate lasers are key elements for future high-speed optical communications systems and all-optical logic circuits.[1,2] Actively mode-locked lasers are promising candidates, especially when synchronization between optical and electrical signals is required. Lithium niobate modulators have been used extensively, but because of their large polarization dependence they require cavities that are built from polarization-preserving fiber components so that environmental instabilities are avoided.[3,4] Similarly, the use of lightly or moderately doped Er fiber for gain results in long cavities and, consequently, drift and pulse-train loss unless careful temperature stabilization is ensured. Semiconductor optical amplifiers (SOA's) can be used in mode-locked laser sources to provide both gain over a broad tuning range and modulation owing to their fast gain dynamics. SOA devices are ideal in these respects because they can offer nearly polarization-independent gain, and, because they can have short pigtails and can combine the gain and modulation functions, they can in principle result in short and environmentally stable cavities. SOA's have been used to gain modulated fiber laser cavities with external optical pulse trains, but these cavities also included Er fiber to provide the gain. This technique was used to demonstrate mode locking in a semiconductor ring cavity.[5] In a recent experiment a sophisticated oscillator cavity employing heavily doped Er fiber and a SOA were used to show all-optical packet storage and active mode locking at 10 GHz.[6] Monolithic laser diodes incorporating gain and saturable absorption sections were also injection mode locked to produce high-repetition-rate short-pulse sources.[7,8] These lasers, however, are research devices and are not widely available, and wavelength tuning requires tunable injection sources. In this Letter we demonstrate an actively mode-locked fiber ring laser that uses a single intracavity active SOA element to provide both gain and gain modulation. The gain modulation of the SOA is provided by cross-gain saturation from an external gain-switched distributed-feedback (DFB) pulse train. One consequence of using a cavity with a single active optically modulated SOA is its ability to produce pulses that are mode locked at a harmonic repetition frequency to that of the external signal. Repetition-frequency multiplication by rational-harmonic mode locking has been used in mode-locked laser diodes,[7] all-optical storage loops,[9] and external-cavity semiconductor laser[10] and fiber laser sources.[11,12] Here the optical modulation of the SOA by a short gain-switched laser pulse is particularly advantageous, as it leads to shorter pulses from the mode-locked cavity and was used to extend the operation of the source to 20 GHz. The source provides nearly transform-limited 4.3-ps pulses at 10 and 20 GHz over a 16-nm tuning range and is nearly environmentally insensitive. Furthermore, the source is simple to build and was constructed entirely from commercially available standard fiber pigtailed components.

Figure 1 shows the experimental configuration. Gain was provided by a 500-μm bulk InGaAsP–InP ridge waveguide SOA with antireflection-coated facets, angled at 10°. The SOA had a peak gain at 1535 nm and a 400-ps recovery time and could provide 23-dB small-signal gain with 250-mA dc drive current. We used Faraday isolators at the input and output of the SOA to ensure unidirectional oscillation in the ring and to stop the externally introduced signal from circulating in the cavity. Immediately after the SOA a 3-dB fused optical fiber coupler was used to insert the external signal and to extract the mode-locked pulse

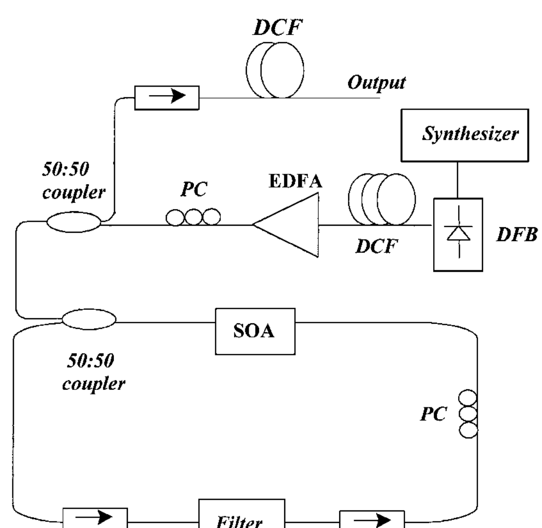

Fig. 1. Experimental layout: PC's, polarization controllers. See text for other definitions.

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trains. A tunable filter with a 5-nm bandwidth was used for wavelength selection. The SOA exhibited a 2-dB polarization gain dependence, and a polarization controller was inserted into its input port. Adjustment of the polarization controller was required only at the beginning of a session for optimum pulse quality, and no further adjustments were required during operation. The total length of the ring cavity was 14.5 m, corresponding to a 13.79-MHz fundamental frequency, but could be significantly reduced. The externally introduced pulses were generated from a 10-GHz gain-switched DFB laser diode operating at 1548.5 nm. These pulses were compressed to 15 ps with dispersion-compensation fiber (DCF) before being amplified in an erbium-doped fiber amplifier (EDFA) and injected into the ring cavity. A polarization controller was used to control the polarization state of the gain-switched pulses before entry into the ring, and again adjustment was required only for optimization.

In the absence of the external gain-switched pulse train the fiber ring laser source runs cw and is tuned from 1523 to 1576 nm, providing approximately constant 400-μW output power across its tuning range. With the DFB gain switched at ~10 GHz, at a frequency equal to a harmonic of the fiber ring oscillator and with the EDFA adjusted to provide 400 μW of optical power into the cavity and corresponding to 40-fJ pulse energy, the ring laser source breaks into stable, mode-locked operation. Figure 2(a) shows the 10-GHz pulse train, monitored with an optical sampling oscilloscope (Hamamatsu OOS-01). Frequency detuning of the microwave signal generator from a SOA cavity harmonic by one half of the fundamental cavity frequency and an increase of the optical power provided by the EDFA to ~500 μW causes the laser to mode lock at 20 GHz. Figure 2(b) shows the corresponding pulse train at 20 GHz. The output pulses were also monitored on a second-harmonic autocorrelator and were found to have an 8-ps duration at either repetition rate and to be non-transform limited. The extra frequency chirp that resulted primarily from the saturation of the SOA was compensated for at the output of the laser with dispersion-compensating fiber of −11.4 ps/nm dispersion. Figure 2(c) shows the autocorrelation trace of the pulse train at 20 GHz, obtained at 1541.6 nm. The trace was fitted with the autocorrelation of a squared hyperbolic secant profile of 4.3-pulse width [white dots in Fig. 2(c)] and shows a good fit. Figure 2(d) shows the corresponding optical spectrum. The indicated pulse-width–bandwidth product of the output was 0.34, close to that of a transform-limited squared hyperbolic secant profile. Figure 3 shows the change of the pulse width and the average optical power of the mode-locked source versus wavelength when the source was operated at 20 GHz, indicating a nearly constant pulse width across its 16-nm tuning range. Similar results were obtained when the source was mode locked at 10 GHz. The results were obtained easily, and both polarization controllers were necessary only for detailed optimization.

The mode-locking process was studied by measurement of the relative time delay at which the mode-locked pulse forms behind the external pulse and the development of a detailed analytical model. The timing measurements of the external pulse were performed on the amplified spontaneous emission signal emerging from the cavity with the oscillation blocked. Mode locking results from the periodic gain modulation caused by the fast saturation of the SOA from the external pulse and the subsequent relatively slow gain recovery, followed by new saturation as the mode-locked pulse transits the SOA. These results define a short temporal window within which the mode-locked pulse can form. The mode-locked pulse forms behind the external pulse at the point at which the recovered gain exceeds the cavity losses. The key parameters that determine the precise pulse width and position at which the mode-locked pulse forms are the small-signal gain and recovery time of the SOA, cavity losses, energy, and pulse width of the external modulating pulses. During operation only the SOA gain and energy of the external pulse can be varied easily. It was found both experimentally and theoretically that minimum pulse widths are obtained when these parameters are adjusted so that the mode-locked pulse forms in the middle between two successive external pulses. This condition was

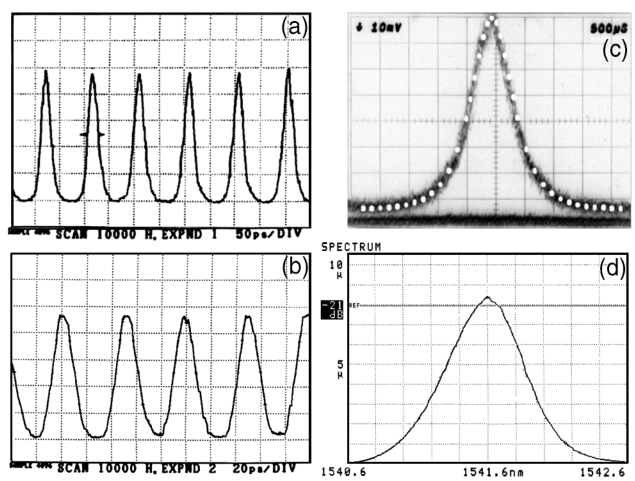

Fig. 2. (a) 10-GHz optical pulse train, (b) 20-GHz optical pulse train. (c) Second-harmonic autocorrelation trace obtained at 20 GHz, showing a 4.3-ps pulse, assuming a hyperbolic secant profile. The time base corresponds to 4.15 ps. (d) Optical spectrum of the mode-locked pulses.

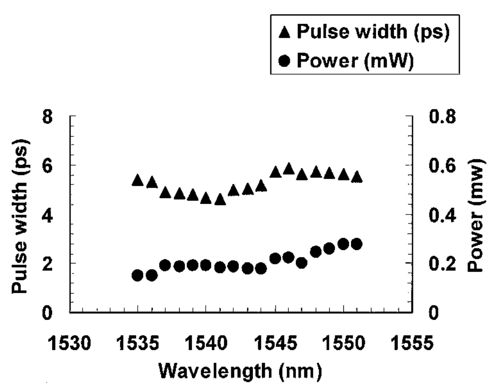

Fig. 3. Tuning curves for pulse width and average power of the mode-locked pulses at 20 GHz.

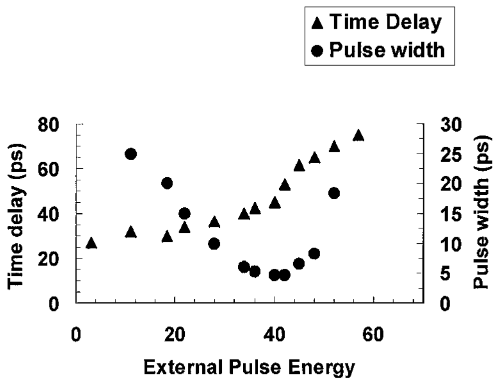

Fig. 4. Pulse width and relative time delay of the mode-locked pulses behind the external pulse versus external-pulse energy.

found to correspond to the case in which the pulse energies of the external and the mode-locked pulses are similar. A decrease of the external-pulse energy or an increase in the SOA gain results in higher gain in front of the mode-locked pulse that consequently shifts it toward the first external pulse. An increase of the external-pulse energy or a decrease of the SOA gain has the opposite effect, with the mode-locked pulse trailing toward the second external pulse. In either case the width of the mode-locked pulse increases. Figure 4 shows the pulse width and the relative delay by which the mode-locked pulse forms behind the external pulse at 10 GHz as the external-pulse energy is varied. Figure 4 shows that the point of minimum pulse width is relatively insensitive to the external-pulse energy, as 20-fJ variation caused only a 50% pulse broadening.

Performance degradation of actively mode-locked fiber lasers is due to (a) rotation of the polarization state of the optical field owing to environmental change, resulting in degradation of the performance of polarization sensitive devices, and (b) cavity-length drift owing to the temperature dependence of the refractive index of glass. To examine the dependence on the polarization state of both external and recirculating signals we adjusted both controllers away from their optimum position. This resulted in a variation of as much as 20% in the output power and a 25% pulse broadening, but at no time was there a mode-locked pulse-train loss. This variation represents mild degradation of the performance of the system and is due to the low polarization gain dependence of the SOA in the saturated regime. Clearly a polarization-independent SOA would remove this variation altogether. To examine the sensitivity of the oscillator to temperature variations we also measured the rf bandwidth over which the ring oscillator mode locked as the repetition frequency of the external pulse train was varied. This bandwidth was found to be 400 kHz, corresponding to 2.7-ps variation in the round-trip time of the ring cavity. By comparison the differential time delay in the cavity round-trip time owing to the temperature dependence of the refractive index in the core of the fiber was only 0.6 ps, with a 2 °C temperature variation and assuming a 20 ps/km °C temperature-dependent differential delay coefficient for the fiber.

In summary, we have presented a simple and stable actively mode-locked fiber laser that uses a single SOA for gain and modulation. With this technique it was possible to demonstrate nearly transform-limited 4.3-ps pulse trains at 10 and 20 GHz over a 16-nm tuning range.

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References

1. K. L. Hall and K. A. Rauschenbach, Opt. Lett. **23,** 1271 (1998).
2. T. J. Xia, Y. Liang, K. H. Ahn, J. W. Lou, O. Boyraz, Y. H. Kao, X. D. Cao, S. Chaikamnerd, J. K. Andersen, and M. N. Islam, IEEE Photon. Technol. Lett. **10,** 153 (1998).
3. Th. Pfeiffer and G. Veith, Electron. Lett. **29,** 1849 (1993).
4. H. Takara, S. Kawanishi, M. Saruwatari, and K. Noguchi, Electron. Lett. **28,** 2095 (1992).
5. D. M. Patrick, Electron. Lett. **30,** 43 (1994).
6. K. L. Hall, J. D. Moores, K. A. Rauschenbach, W. S. Wong, E. P. Ippen, and H. A. Haus, IEEE Photon. Technol. Lett. **7,** 1093 (1995).
7. X. Wang, H. Yokoyama, and T. Shimizu, IEEE Photon. Technol. Lett. **8,** 617 (1996).
8. C. Schmidt, E. Dietrich, S. Diez, H. J. Ehrke, U. Feiste, L. Kuller, R. Ludwig, and H. G. Weber, in *Digest of Conference on Lasers and Electro-Optics* (Optical Society of America, Washington D.C., 1999), paper CThA3.
9. J. D. Moores, W. S. Wong, and K. L. Hall, Opt. Lett. **20,** 254 (1995).
10. N. Onodera, A. J. Lowery, L. Zhai, Z. Ahmed, and R. S. Tucker, Appl. Phys. Lett. **62,** 1329 (1993).
11. N. A. Whitaker, H. Houh, and H. Avramopoulos, in *Digest of IEEE Lasers and Electro-Optics Society 1990 Annual Meeting* (Institute of Electrical and Electronics Engineers, New York, 1990), paper MO03.
12. E. Yoshida and M. Nakazawa, Electron. Lett. **32,** 1370 (1996).